THE SOLAR CONSTANT OF RADIATION.[1]

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If we had no eyes we should still know of the sun by the feeling of warmth. The intensity of solar rays in any part of the spectrum can be measured by delicate thermometry. Vision and photography are both restricted within comparatively narrow limits of wave-length, and each differs in its sensitiveness from wave-length to wave-length. Ultra-violet, visible and invisible red rays, however, all produce their just and proportional influences on the bolometer, or thermopile. This is not universally known, and there are still many who suppose we should distinguish between so-called actinic, visible and heat rays. Doubt has been expressed, for instance, whether bolometric measurements give true indications of the intensity of those rays which promote plant growth. Such doubts are not justified, and we may expect very valuable results in the future from the application of the spectro-bolometer to the interesting questions of radiation and plant physiology.

We use heat units to express the intensity of solar radiation. The solar constant of radiation may be defined closely enough as the number of degrees by which one gram of water at 15° centigrade would be raised, if there should be used to heat it all the solar radiation which would pass at right angles in one minute through an opening one centimeter square, located in free space, at the earth's mean solar distance. Experiments were begun about 1835 by Pouillet and by Sir John Herschel for the measurement of this great constant of nature. The investigation has been continued by Forbes, Crova, Violle, Radau, Langley, K. Ångström, Chwolson, W. A. Michelson, Rizzo, Hansky, Scheiner and others. It is an indication of the great difficulty of the research that entire uncer-

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tainty as to the value of the solar constant of radiation between the limits of Pouillet's value, 1.76 calories, and Ångström's value, 4.0 calories per square centimeter per minute, prevailed at the beginning of the twentieth century.

Professor Pringsheim has collected the following table[2] of solar-constant values, as determined by different observers:

Year.	Observer.	Calories.	Year.	Observer.	Calories.
1837	Pouillet	1.8	1889	Pernter	3.2
1860	Hagen	1.9	1896	Vallot	1.7
1872	Forbes	2.8	1897	Crover and Hansky	3.4
1875	Violle	2.6	1898	Rizzo	2.5
1878	Crova	2.3	1908	Scheiner	2.3
1884	Langley	3.1	1908	Abbot and Fowle	2.1[3]
1889	Sawelief	2.9			

He omits Ångström's 4.0, published in 1890 and withdrawn in 1900, but which is even yet sometimes quoted. He omits also Very's 3.1, published in 1901 and independently obtained in 1910. Recently published values of Kimball, Gorczynski and others, approximately 2.0, are based in part on work of Abbot and Fowle.

The determination of the solar constant involves: (1) correct measurements of the heat equivalent of the solar radiation at the earth's surface; (2) a correct estimate of the losses which the rays have suffered in the atmosphere before they reached the measuring apparatus. We shall now discuss these two branches of the work.

Pouillet invented, about 1835, his well-known instrument, the pyrheliometer, for measuring the solar rays at the earth's surface. Many criticisms have been justly made in regard to the accuracy of this pioneer instrument, and attempts have been made by many to improve on it, or to substitute a better. In our practice at the Smithsonian Astrophysical Observatory, we have substituted a silver disk for Pouillet's water chamber; inserted a cylindrical bulb thermometer, radially instead of axially, in the disk; provided a metal-lined wooden chamber to screen the instrument from the wind; and added convenient adjuncts for shading and exposing the instru-

[2] "Physik der Sonne," p. 417.

[3] This value was expressed in terms of a provisional scale of pyrheliometry which has since been proved too high.

ment.[4] Finally we have ceased to regard our instrument as giving more than relative measurements. It is only a secondary pyrheliometer for convenient use. We standardize its readings by comparison with an absolute pyrheliometer of another kind.

No known substance absorbs radiation perfectly at a single encounter. Kirchhoff showed, fifty years ago, that a hollow chamber must absorb perfectly, because of the opportunity for an infinite number of absorption encounters within it. W. A. Michelson, in 1894, invented a standard pyrheliometer including a hollow chamber with a narrow opening for the admission of rays. The walls of the chamber were bathed by a mixture of ice and water, and the heating effect of the solar rays was measured by the amount of ice melted, which was determined by noting the expansion in volume of the mixture of ice and water.

Nearly ten years later, being ignorant of Michelson's pyrheliometer (which was described in the Russian language), it occurred to me also to employ a hollow receiving chamber. I proposed to measure the solar heating produced in it by bathing its walls with flowing water, and determining the rate of flow and rise of temperature of the water. After experiments lasting intermittently from 1904 to 1910, I am now satisfied that this device has proved successful, and that we have truly an absolute standard pyrheliometer. With the aid of my colleagues, Mr. Aldrich and Mr. Fowle, two of these water-flow pyrheliometers were carefully tested last year.[5] Not only did they agree in measurements of solar radiation, but test quantities of heat introduced electrically within the absorbing chambers were accurately recorded by the methods ordinarily used to measure solar heating. We believe of the absolute water-flow pyrheliometer, it gives the intensity of solar radiation at the earth's surface in calories per square centimeter per minute within a probable error of 0.2 per cent. For convenience we make our daily observations with secondary silver-disk pyrheliometers, which have been standardized against the absolute water-flow pyrheliometer.

[4] See Abbot, "The Silver Disk Pyrheliometer," *Smithson. Misc. Coll.*, Vol. 56, No. 19, 1911.

[5] See Abbot and Aldrich, *Astrophys. Journal*, Vol. XXXIII., 125, 1911.

Having perfected the standard and secondary pyrheliometers to a satisfactory degree of accuracy and durability, the first branch of solar-constant work is accomplished by reading with the silver-disk pyrheliometer at the earth's surface, and reducing its indications to calories per square centimeter per minute. We now turn to the discussion of the second branch of the work, namely the estimation of the transmission of the atmosphere for radiation.

Lambert and Bouguer showed almost simultaneously, about 1760, that the transmission of light through a homogeneous medium may be expressed by an exponential formula, such as:

$$E = E_0 a^m.$$

Here E is the intensity transmitted, E_0 the original intensity, a the fraction transmitted by unit thickness, and m the actual thickness of the transparent medium.

Pouillet applied Bouguer's formula to the atmosphere. As the atmosphere is not homogeneous, but decreases in turbidity and density from the earth's surface upward, this would seem at first sight unjustified. But if we consider unit thickness to be the thickness of the atmosphere traversed by a vertical beam, then as the ray departs from the vertical, it still shines through every layer which it did at first, and the path in every layer increases nearly as the secant of the zenith distance of the ray. Under these circumstances it can be shown that (subject to certain limitations to be mentioned) the exponential formula given above should hold, if we consider E to be the intensity at the earth's surface, E_0 the intensity outside the atmosphere, a the transmission coefficient for a vertical beam, and m the secant of the sun's zenith distance.[6]

Owing to atmospheric refraction, the fractional increase in path of the ray, as the zenith distance waxes, tends to be greater for the outer layers of the atmosphere than for its inner ones. On the other hand, the curvature of the earth's surface produces an opposite tendency. But for zenith distances less than 70° these effects may be neglected, and they are hardly worth considering at 75°

[6] See *Annals Smithson. Astrophys. Obser.*, Vol. II., p. 14, 1908.

zenith distance.[7] Solar-constant determinations require no higher values of zenith distance than these to be considered.

Radau and Langley proved the necessity of confining the atmospheric use of Bouguer's formula to approximately monochromatic rays. In general, for a reason which Lord Rayleigh has shown, the transmission of the atmosphere increases gradually with increasing wave-lengths. Thus in the violet the transmission for a vertical ray to sea level may be 50 per cent., and for a deep red ray 80 per cent. But besides this gradual change there are also spectral regions of almost complete absorption by atmospheric oxygen, and by water-vapor, so that in these regions the transmission approaches zero. If we should disregard these differences, and determine the constants of the exponential formula above, by pyrheliometric measurements alone at different solar zenith distances, our result E_0 for the intensity outside the atmosphere must necessarily be too small.[8]

Langley was the first to act upon this, and to devise apparatus and methods for measuring the energy and the atmospheric transmission at all parts of the spectrum. For this purpose he invented the bolometer about 1880, and automatic registration of its indications about 1890. As we now use it the bolometer comprises two similar tapes of platinum, each about 1 cm. long, 0.01 cm. wide and 0.001 cm. thick. These are coated with lamp-black by smoking over a camphor flame. They lie parallel to the spectrum lines, and about 0.8 cm. apart. One tape may be shined upon by the rays, the other can not. Hence the heat absorbed from a narrow region of spectrum, usually about twice the extent comprised between the D lines, raises the temperature of the exposed tape with reference to the other. The two tapes and two resistance coils are combined to form a Wheatstone's bridge, and the rise of temperature produced as above stated deflects a sensitive galvanometer. The galvanometer needle reflects a tiny spot of light on a photographic plate, which moves vertically as driven by clock work. The same clock work moves the spectrum slowly over the bolometer tape. In this way may be produced in from eight to twelve minutes, according to the spectroscopic outfit employed, a bolograph, or spectrum energy

[7] *Loc. cit.*, p. 59.
[8] *Loc. cit.*, p. 16.

curve, extending from about wave-length 0.30 μ in the ultra-violet to about wave-length 3.0μ in the infra-red. Its ordinates are deflections of the galvanometer, proportional to energy in the spectrum, and its abscissæ are proportional to differences of prismatic deviation. The Fraunhofer lines, and great oxygen and water-vapor bands, show as depressions in the curve. In order to eliminate distortions which are due to differences, for differing wave-lengths, in the reflecting power and transmission of the mirrors and prism used in the optical train, special investigations of the transmission of the apparatus are made from time to time, and the curves corrected accordingly.

In our ordinary practice, from six to eight bolographs are taken in a single forenoon, between the times when the sun's zenith distance is 75° and (say) 30°. The curves are measured at about thirty positions, uniformly spaced in the prismatic spectrum. Each group of six to eight measurements, at a single spectrum place, furnishes means of computing from Bouguer's formula the transmission of the atmosphere for that wave-length, and also the ordinate which would have been found there if the observations had been made outside the atmosphere. The sum of the ordinates measured on any bolograph is approximately proportional to the total energy of all wave-lengths observed. Similarly the sum of the ordinates computed for outside the atmosphere is proportional to the total energy there.[9]

In order to reduce the total energy, as determined bolometrically, to calories per square centimeter per minute, the pyrheliometer is read, while the spectro-bolometric work is in progress, on each day of observation. Thus a factor is obtained for deducing from the areas of the bolometric curves the true heat units corresponding.[10] A complete determination of the solar constant of radiation requires

[9] In the regions of great water-vapor and oxygen absorption the extra-atmospheric curve is determined by interpolation between adjacent comparatively unaffected wave-lengths on either side, for we know that there is no oxygen or water-vapor absorption of these bands produced in the sun, so that they ought not to show in the extra-atmospheric curve. Small allowances are also made for the energy of lesser and greater wave-lengths than any observed.

[10] For further details consult *Annals,* Vol. II.

about three hours of observation, under a cloudless and uniformly clear sky, and about three days of computing.

We began to make solar-constant observations in Washington at the Smithsonian Astrophysical Observatory, in October, 1902, and continued them there whenever a favorable opportunity was presented, until May, 1907. In all this time we made only 44 tolerably satisfactory determinations at Washington, for cloudless days were rare, and many days that promised fairly proved disappointing, by reason of the appearance of smoke, haze or clouds. Four important results came from the Washington observations. First, no apparently good determinations yielded solar-constant values above 2.38 of our then provisionally adopted scale of calories, or 2.25 true calories. Second, the mean value in the true calories from 44 determinations was 1.960. Third, the transmission of the atmosphere was determined on many days, and for many wave-lengths.[11] Fourth, a strong probability was raised by the results of observations of 1903 that the sun is a variable star.[12] This variation seemed to reach 10 per cent. in its extreme range, but no tendency towards a regular period was then found for it. A dependent variation in terrestrial temperatures seemed indicated.

Primarily in order to make spectro-bolometric determinations of the solar constant, suitable to test the supposed variability of the sun, an expedition under my charge went out to Mount Wilson in 1905, by invitation of Director Hale of the Mount Wilson Solar Observatory. The site proved excellent for the purpose, on account of its considerable altitude, cloudless sky and freedom from wind. Much aid and comfort was furnished by Director Hale and his staff. The expedition was repeated in 1906, 1908, 1909 and 1910. We now occupy a cement observing shelter and living quarters there, on ground leased from the Solar Observatory. Our observations have generally occupied the six months, May 15 to November 15, and in the last years we have made practically daily determinations of the solar constant of radiation during this interval.

[11] Astronomers have not yet very generally availed themselves of the accurate coefficients of atmospheric transmission obtained in our researches for all parts of the spectrum, and from Washington, Mount Whitney and Mount Wilson.

[12] See S. P. Langley, *Astrophysical Journal,* Vol. 19, p. 305, 1904.

It was thought doubtful by Langley, and others, if correct estimates of the atmospheric transmission can be made, even by the spectro-bolometric method of high and low sun observations. Langley, indeed, gave an argument tending to show that the values of the solar constant thus obtained fall far below the true intensity of the solar radiation outside the atmosphere. This argument, however, seems to be unsound.[13] In order to test the accuracy of the method I made spectro-bolometric measurements on Mount Whitney (4420 meters elevation) in 1909 and 1910 simultaneously with similar observations made by Messrs. Ingersoll and Fowle, respectively, on Mount Wilson (1800 meters elevation). In 1905 and 1906 solar-constant measurements were made nearly simultaneously at Mount Wilson and at Washington (10 meters elevation). It does not appear from these observations that there are any differences in the solar-constant values depending on the altitude of the observer, and not due to accidental errors of observations.[14]

In illustration of this conclusion I give the results obtained simultaneously at Mount Wilson and Mount Whitney:

Date.	1909, Sept. 3.	1910, Aug. 12.	1910, Aug. 13.	1910, Aug. 14.
Mount Wilson.........	1.943	1.943	1.924	1.904
Mount Whitney........	1.959	1.979	1.933	1.956

The very slight excess of the Mt. Whitney values is not large enough to be significant.

We conclude that the solar-constant values computed from the method of high and low sun observations do not depend on the altitude of the observing station up to altitudes of 4,420 meters, provided the sky conditions are satisfactorily clear and uniform.

Reducing values published in Vol. II. of the *Annals* to standard calories at 15° centigrade, and including the mean values obtained in later years,[15] we have:

[13] See *Annals,* Vol. II., pp. 119–121.

[14] As regards the Washington and Mount Wilson comparisons, see *Annals,* Vol. II., pp. 99 and 102. Note that the provisional scale of these *Annals* values is 5 per cent. too high.

[15] Many of the values of 1910 are not yet reduced.

SOLAR-CONSTANT MEAN VALUES.

Place.	Washington.	Mount Wilson.					Mount Whitney.	
Date.	1902–1907	1905	1906	1908	1909	1910	1909	1910
Times observed........	44	59	62	113	95	28	1	3
Mean value............	1.960	1.925	1.921	1.929	1.896	1.914	1.959	1.956

Our observations indicate as the mean value of the solar constant of radiation:

1.922 calories (15° C.) per square centimeter per minute.

The observations having been obtained mainly near the time of sun-spot maximum we think it probable that their mean is hardly high enough to represent the average condition of the sun. We incline to think this because it has been shown by Koppen, Nordmann, Newcomb, Abbot and Fowle, Bigelow, Arctowski and others that the earth's temperature is a little lower at sun-spot maximum than at sun-spot minimum. This probable correction cannot exceed one or two per cent.

There is another reason why our value of the solar constant may be too low. We have not been able to observe, even on Mount Whitney, any radiation beyond the wave-length 0.29μ in the ultra-violet spectrum. Whether the rays of less wave-length are obliterated in the earth's atmosphere or in that of the sun we cannot know, but we do know that ozone, which is perhaps formed in the upper atmosphere, exercises powerful selective absorption beyond wave-length 0.29μ. Hence it may be that we are forced to neglect some radiation not quite negligible. It is very improbable that the amount thus neglected exceeds 1 or 2 per cent.

As for the supposed variability of the sun, our determinations strongly indicate that the so-called solar constant is not really a constant, but fluctuates over a range of about 8 per cent. This result is apparently the direct outcome of our observations, but the question may well be asked if the apparent fluctuation is not due either to the inaccuracy of the observations or to incorrect estimates of the transmission of the atmosphere. If it were due merely to accidental errors of observations, a gradual march, step by step, day by day, from a low value to a high one and return would be the ex-

ception. We find it to be the rule, hence we must exclude accidental errors as the main source of the apparent variability of the sun. As for the other explanation suggested, we find no material difference in the result derived for the solar constant on a good day whether we observe at sea-level, at one mile, or at nearly three miles elevation, though the pyrheliometer readings on the ground differ by 25 per cent. between Washington and Mount Whitney. Hence we may reasonably conclude that we do, in fact, correctly estimate the loss which occurs in the atmosphere. The fluctuation in the solar-constant results therefore seems to indicate either a true variability of the sun, or else the interposition of meteoric dust, or other cosmic hindrance to the passage of radiation from the sun to the earth. These fluctuations, while not of regular periodicity, generally run their courses within five or ten days.[16]

It is now proposed to test this conclusion by conducting solar-constant measurements simultaneously at Mount Wilson and in southern Mexico. If the results of a long series of daily observations at these remote stations should agree, it would seem quite unlikely that any apparently simultaneous fluctuations of the solar constant of radiation could be attributed to terrestrial influences.

Summary.

Special apparatus, including the silver-disk secondary pyrheliometer, the absolute water-flow pyrheliometer and the recording spectro-bolometer, has been employed by the writer and his colleagues at Washington and Mount Wilson and Mount Whitney, to determine the mean value of the solar constant of radiation, and its possible fluctuations.

The observations, exceeding 400 in number, have been made in all the years since 1902 to 1910, but most plentifully and accurately in 1908, 1909 and 1910. The mean value of the intensity of solar radiation outside the atmosphere, at mean solar distance, is found to be 1.922 (15°C.) calories per square centimeter per minute, but might prove 1 or 2 per cent. higher in years of less sun-spot activity. The solar-constant values do not appear to depend on the altitude of

[16] See Abbot and Fowle, *Astrophysical Journal*, April, 1911.

the observing station, up to the highest altitude tested, 4,420 meters. Fluctuations in the values proceeding step by step, day by day, from higher to lower values and return, within a range of about 8 per cent. usually occur in somewhat irregular intervals of from five to ten days in total period. These fluctuations are thought to indicate a true variability of the sun. It is proposed to test this conclusion by daily observations extending over several months, and to be made simultaneously in California and southern Mexico.